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PRELIMINARY OARE ABSOLUTE ACCELERATION MEASUREMENTS ON STS-50

ROBERT C. BLANCHARD

JOHN Y. NICHOLSON

JAMES R. RITTER

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Langley Research Center
Hampton, Virginia 23681-0001

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Robert C. Blanchard
NASA Langley Research Center
Hampton, Virginia 23681-0001

John Y. Nicholson
ViGYAN, Inc.
Hampton, Virginia 23666-1325

James R. Ritter
Lockheed Engineering & Sciences Co.
Hampton, Virginia 23666-1339

Abstract

Orbital Acceleration Research Experiment (OARE) data on STS-50 have been examined in detail during a 2-day time period. Absolute acceleration levels have been derived at the OARE location, the orbiter center-of-gravity, and at the STS-50 spacelab Crystal Growth Facility.

The tri-axial OARE raw acceleration measurements (i.e., telemetered data) during the interval have been filtered using a sliding trimmed mean filter in order to remove large acceleration spikes (e.g., thrusters) and reduce the noise. Twelve OARE measured biases in each acceleration channel during the 2-day interval have been analyzed and applied to the filtered data. Similarly, the *in situ* measured x-axis scale factors in the sensor's most sensitive range were also analyzed and applied to the data. Due to equipment problem(s) on this flight, both y- and z- axis sensitive range scale factors were determined in a separate process (using the OARE maneuver data) and subsequently applied to the data. All known significant low-frequency corrections at the OARE location (i.e., both vertical and horizontal gravity-gradient, and rotational effects) were removed from the filtered data in order to produce the acceleration components at the orbiter's center-of-gravity, which are the aerodynamic signals along each body axes. Results

indicate that there is a force of unknown origin being applied to the Orbiter in addition to the aerodynamic forces. The OARE instrument and all known gravitational and electromagnetic forces have been reexamined, but none produce the observed effect. Thus, it is tentatively concluded that the Orbiter is creating the environment observed.

Nomenclature

A	=acceleration
g	=gravitational acceleration at sea level (9.80665 m/s^2)
MET	=mission elapsed time (i.e., time from lift-off)
nano-g	$=1 \times 10^{-9} \text{ g}$
p, q, r	=body axes angular rates
T	=temperature
u, v, w	= air relative velocity body axes components
V	=velocity
V _{air}	=air relative velocity
X, Y, Z	=sensor axes
X _b , Y _b , Z _b	=body axes
α	=angle-of-attack
β	=side-slip angle
μg	$=1 \times 10^{-6} \text{ g}$

Subscripts

o	=Orbiter spacecraft coordinates
L	=with respect to the center-of-gravity
rot	=rotational

Acronyms

CAS	=Calibrated Ancillary System
CGF	=Crystal Growth Facility
HiRAP	=High Resolution Accelerometer Package
IMU	=Inertial Navigation Unit
OARE	=Orbital Acceleration Research Experiment
STS	=Space Transportation System

Introduction

The Orbital Acceleration Research Experiment (OARE) consists of a three axis, state-of-the-art accelerometer with an electrostatically suspended proof mass, a full in-flight calibration station, and a microprocessor which is used for in-flight experiment control, processing, and storage of flight data. The experiment system is designed to measure low-frequency (<1 Hz) low-level acceleration (i.e., nano-g sensitivity). An in-depth description of the experiment goals, equipment design characteristics, and capabilities is given in Ref. 1.

The first Shuttle flight of the OARE was June 5, 1991, on the *Columbia* during STS-40. Orbital data were collected for about 3.5 days beginning approximately 5.5 days after launch for this mission. Some equipment problems were noted on the first OARE flight; however, limited results were obtained. These results are given in reference 2.

After the STS-40 flight, the OARE was removed and the problems were isolated and repaired prior to the STS-50 flight. STS-50 is the first flight which employs an operating nano-g sensor coupled with a calibration capability which allows for the measurement of absolute acceleration levels. Over 13 days of orbital data were collected on STS-50. This included over 60 full calibrations sequences which provided both bias and scale factor measurements for 3 axes and 3 ranges. A problem, however, was noted in the most sensitive range for the scale factor measurements on the y- and z-axes. To circumvent the anomaly, OARE maneuvers (three separate rotations about each of the Orbiter's body axes) have been used to provide scale factors for all three axes in the sensor's most sensitive range.

This paper presents the analysis of the OARE data taken during the time period 1^d 14^h to 3^d 14^h MET. The analysis of this orbital time segment was selected in order to provide low frequency, low acceleration information for

spacelab furnace experimentation application, e.g. the Crystal Growth Facility. The on-orbit calibration measurements and their applications to the OARE acceleration signals to produce absolute accelerations are discussed. Also presented is the transformation of the data from the OARE location to the orbiter's center-of-gravity, which provides acceleration data on the drag aerodynamics along each axis.

Flight Data Analysis

Orbiter State Parameters

Ancillary flight data of the Orbiter's inertial position, velocity vector, and orientation (Aries mean 1950 coordinate system) are received from Goddard Space Flight Center in the form of Calibrated Ancillary System (CAS) tapes. In general, these data give the conditions under which the OARE acceleration measurements were taken. Specifically, the CAS data are interpreted in order to validate the OARE data and to transform the OARE data to other locations (e.g., the center-of-gravity). The CAS data are transformed into other useful quantities, such as distance from the center of Earth, latitude, longitude, and relative velocity. For relative velocity calculations, it is assumed that the atmosphere is rotating with the Earth. On the CAS tapes, the orientation of the Orbiter is given in quaternions. These are combined with the velocity components to calculate angle of attack, α , and sideslip angle, β . This section gives some of the results from the Orbiter CAS tapes.

Figure 1 shows the relative velocity and the altitude variations as a function of MET in hours. The altitude is referenced to a spherical Earth with a radius of 6356.766 km. As seen, the orbit is very circular; a difference of only 9 km exists between perigee and apogee. The altitude range is about 325 km to 316 km and the orbit is slightly changing with time. The expected mean aerodynamic drag is very small and the 90 min. variation due to the slightly elliptical orbit is even smaller

(e.g., using the 1976 U.S. standard atmosphere,³ the acceleration signal is estimated at about 275 ng with a variation of ± 25 nano-g).

Based upon the CAS data, the Orbiter is oriented with the payload bay doors toward the velocity vector with the right wing tilted about 12° into the velocity vector (i.e., forward of a line perpendicular to the orbital plane). The orientation is shown in Fig. 2 where the engines are pointed toward Earth and the payload doors are open. The insert graph in Fig. 2 shows the α and β flight data for the entire period. Both angles are tightly held to $\pm 1/2$ deg centered around $\alpha = -90^\circ$ and $\beta = 12^\circ$. For completeness, the definitions⁴ of α and β are as follows:

$$\alpha = \tan^{-1}(w/u) \text{ and}$$

$$\beta = \sin^{-1}(v/V_{\text{air}}),$$

where u , v , and w are body axes velocity components of V_{air} and V_{air} is the magnitude.

In this orientation, it is anticipated that the majority of the aerodynamic effect is along the positive z -body axis. The y -body axis acceleration should be negative and very small due to an aerodynamic force produced on the right side of the Orbiter facing into the velocity vector. The x -body axis acceleration signal should be positive, almost entirely due to gravity-gradient and rotational effects. Figure 2 also shows the body axis coordinate system.

Figure 3 shows the Orbiter's three body rates during the entire period. Clearly, roll rate, p (the angular rate about the x -body axis) is on the average nearly zero. If the Orbiter y -body axis were held perpendicular to the orbital plane, the pitch rate, q , (the angular rate about the y axis) would be equivalent to rotating the Orbiter 360° over the orbital period of 90 minutes (i.e., 0.067 deg/s). The y axis is not quite perpendicular to the orbital plane so that this rate component is slightly reduced. The yaw rate, r , (the angular rate about the z axis) shows an approximate value of $.014$ deg/s due to the 12° offset mentioned earlier.

In-flight Calibrations

The success of making low frequency, low amplitude acceleration measurements at orbital altitudes relies heavily on providing reliable calibration factors. The OARE plays a unique role in the technological development of systems for making these calibration measurements. It has a complete calibration station providing both *in situ* bias and scale factor measurements. This section of the report discusses the instrument operating conditions and shows the calibration data taken during the interval.

The instrument was programmed to perform a calibration sequence approximately every 4.75 hours. The calibration sequence includes up to nine separate bias calibrations (three axes, three ranges) and up to six scale factor calibrations (two table rates/axis, with y and z axes scaled simultaneously). A bias calibration consists of collecting 50 s of data in one position, rotating the sensor 180°, and then collecting data for another 50 s period. The sum of the average of each interval is twice the bias, while the difference is twice the average input signal. A scale factor calibration consists of rotating the sensor at a pre-programmed rate and measuring the acceleration difference between the sensor at rate and the average output at rest. This difference is scaled to the known centripetal acceleration which is a function of the square of the rate (which is measured) and the location of the sensor on the table (which is known). Two table rates are used for each sensor range for linearity checks.

Figure 4 shows the temperature measurements from two thermocouples, one inside the sensor package and one mounted on the base, adjacent to the rotary table surface. Throughout the entire period, the temperature varied by about 4°C, getting cooler as the mission progressed. It is interesting to observe the diurnal variation of about 1°C. This type of variation has the potential to seriously limit the interpretation of pendulous type accelerometer drag variations because typical

bias temperature sensitivity coefficients are 20 to 60 $\mu\text{g}/^\circ\text{C}$ for these instruments. That is, for these accelerometers, it is difficult to separate diurnal drag variations from sensor temperature effects since both effects are in phase. It also has been demonstrated that ground based calibrations of these instruments in a 1-g environment produce significant errors when applied to the micro-gravity environment encountered on orbit.⁵ There are two important reasons why OARE is not seriously affected by this phenomenon. First, *in situ* calibrations are made and thus no extrapolations to space are necessary. Secondly, the OARE bias temperature sensitivity coefficients are very small, typically much less than 1 $\mu\text{g}/^\circ\text{C}$.

Figures 5, 6, and 7 show the results of the x, y, and z body axes bias calibrations, respectively. Included in each figure is the temperature at each calibration point. In addition, each time a bias is performed, the true (i.e., bias independent) signal is simultaneously measured and is shown along with the bias on each graph, labeled "signal". From the graphs, it is clear that the bias correction is only a few μg except for the y axis which is about 7 μg . This is within OARE design specifications. The x axis has the largest temperature sensitivity, about 0.2 $\mu\text{g}/^\circ\text{C}$, while both y and z are an order of magnitude smaller. The discrete signal measurements on each axis give a 12 point sample of the expected Orbiter residual acceleration environment, except for scale factor adjustments. Clearly, the x axis has a relatively large, almost constant 1.0 μg signal, while y axis is less than .5 μg and z axis varies about 0.8 μg . This is useful information for checking the adjustments to the measured signals which are discussed later.

The scale factors for the x-axis in its most sensitive range were successfully measured *in situ* using the two programmed calibration table rates. The low and high table rates produce calibration accelerations of approximately 20 μg and

45 μg , respectively. Figure 8 shows the scale factor results along with the instrument temperature as a function of time. The scale factor temperature sensitivity for this axis, in this temperature interval is about 0.3%/°C. As noted earlier, the *in situ* scale factor measurements for the y- and z-axes in the most sensitive range were unsuccessful. These scale factors were determined using data taken during the OARE maneuvers. This method uses the HiRAP accelerometer data and IMU data to solve for the Orbiter's center-of-gravity. This is then used with the OARE data to solve for the scale factors on all three axes. Table 1 summarizes the scale factor results.

Table 1

AVG. SCALE FACTORS*		
axis	<i>in situ</i>	maneuvers
x	1.03	0.93
y	-	1.06
z	-	0.96

*actual SF($\mu\text{g}/\text{count}$)/design SF($\mu\text{g}/\text{count}$)

The *in situ* x-axis scale factor compares moderately well with the one derived from the maneuvers. Several facts are worth mentioning about the possible source for the differences. First, the OARE maneuver occurred late in the mission (on day 12 MET) when the instrument was at a different temperature (cooler). Second, typically each maneuver involves rotating the spacecraft 360°. Rate motion is obtained from gyro processing during the scale factor extraction process. The gyros require calibration factors which introduce errors.

OARE Ground Processing

OARE collects tri-axial data at the rate of 10 samples/s. The data are filtered through an analog filter and a 6 pole Bessel filter with a cutoff frequency of about 1 Hz. This raw data are too noisy for use in detailed characterization of low frequency analysis.

By design, the raw data are telemetered to ground stations and simultaneously processed on-board by the OARE computer using a "trimmed-mean" filter. Briefly, this filter consists of ordering a window of data (for STS-50, the window size was set at 500 samples) from low to high values. Then, a "q statistic" is calculated which gives a measure of outlier content. From this, a percentage of the "tails" of the data is eliminated. The remainder of the data are averaged and the window slides in time (for STS-50, 25 seconds was chosen). Examination of this data revealed that it was still slightly noisy for the purpose of this report. In addition, a check was required to determine whether the on-board computer was handling the data correctly. Thus, it was decided to ground process the raw telemetered data in the same manner as the on-board computer, except vary the window size. However, after the study, it was evident that the flight data processing algorithm performed as planned.

OARE Location Environment

Figure 9 shows the OARE measured x, y, and z acceleration levels in the Orbiter's body axes system at the OARE location. The data in this figure are the OARE 10 samples/sec telemetered raw (unprocessed) data which have been averaged using a trimmed-mean technique with a window of 200 sec sliding at 25 sec intervals. This digital filter essentially limits frequency observability to less than about 0.0025 Hz. However, this introduces no problems since this frequency is much larger than those associated with orbital phenomena of interest. The data have been corrected with the OARE biases and scale factors.

The x-axis appears to produce the largest signal of about $1 \mu g$ with an oscillatory wave of period 26 hours. The y-axis signal is very small and slightly negative. The average z-axis signal is positive and smaller than the x-axis (about $0.6 \mu g$), and also has an oscillatory signal of about 26 hours which is 180° out of phase with the x axis data.

Center-of-Gravity Environment

The location of the OARE sensor in body axes coordinates relative to the Orbiter's center-of-gravity is $X_b = -1.536m$, $Y_b = -0.0234m$, $Z_b = 1.435m$. Based upon this lever arm and the Orbiter orientation data discussed earlier, the magnitude of the major adjustments, namely, gravity-gradient and rotational effects, is shown in Fig. 10. The gravity-gradient effect includes both vertical and horizontal displacements from the orbiter center-of-gravity. Clearly, the largest correction is on the x axis, about $0.65 \mu g$, with components from gravity-gradient and rotational effects. The total of the y axis corrections is an order of magnitude smaller and its source is mostly rotational effects. The net correction for the z axis is practically zero due to the cancellation of the gravity-gradient effects with the rotational contributions. Applying these adjustments to the data shown in Fig. 9 should theoretically give the accelerations at the orbiter center-of-gravity which are the drag measurements. The results are shown on Fig. 11. Clearly, the value of the residual acceleration along the x axis is much too large to be attributable to acceleration due to aerodynamics. Since the velocity is perpendicular to the x axis, the aerodynamics should be very nearly zero. Further, the signal also has an obvious 26 hours oscillation. The z axis also has this oscillation at about the same frequency. The z axis data contain the 90 min drag oscillation similar to that observed during STS-40². The y axis appears about as expected: namely, a small slightly negative acceleration which is mainly attributable to aerodynamics.

Several physical phenomena associated with a 24-hour period have been investigated, such as oblate Earth, geomagnetically induced forces, solar radiation pressure, etc. However, none of the considerations to date have produced the proper amplitude and frequency. Thus, a possible alternative is that the Orbiter itself is producing the environment being measured by the OARE sensor. Of course, this requires further investigations.

CGF Location Environment

The accelerations caused by this force of unknown origin and the aerodynamic forces are given in Fig. 11. This represents the external forces exerted on the Orbiter at the center-of-gravity. The corresponding accelerations at any other location can be obtained by adding to these measurements the predictions due to gravity-gradient and rotational effects at this location.

The location of the Crystal Growth Facility (CGF) melt location (C. Baugher, MSFC, Private Communications), in Orbiter Project spacecraft coordinates, is $x_0 = 1086.00$ in., $y_0 = -44.39$ in., $z_0 = 395.45$ in.

This corresponds to a lever arm about the center-of-gravity of $X_L = .173$ m, $Y_L = -1.117$ m, $Z_L = -.537$ m. Using this lever arm with the orientation and orbiter rotation rate data from the CAS tapes, the corrections to the CGF location have been calculated and the results are shown in Fig. 12. Shown are the individual components along with the total values along the body axes. The largest correction is about $-0.16 \mu\text{g}$ in the y axis due to gravity-gradient horizontal displacement effects. Both x and z axis corrections are fairly small, namely about -0.07 and $-0.035 \mu\text{g}$, respectively.

Figure 13 shows the final results of the low frequency acceleration environment at the CGF melt location. This is obtained by applying the results shown in Fig. 12 to Fig. 11. The acceleration along the x-axis ($\sim 0.5 \mu\text{g}$) is dominated by the acceleration created by the unknown force, possibly the Orbiter

itself. The expected acceleration due to drag in this axis is much smaller, approximately an order of magnitude less. The acceleration along the y-axis is slightly negative ($\sim 0.2 \mu\text{g}$) due to aerodynamics and horizontal displacement effects. The z-axis acceleration shows the diurnal atmospheric effect. This effect is seen in Fig. 13 as the higher frequency variation within the 26 hour variation caused by the component of the unknown force in the z direction.

Error Estimation

The largest and most important error source along all three axes would be from incorrectly estimating the bias. Consequently, care has been taken with this quantity throughout the analysis. For this study, a simple straight line was fit through the measured bias values. The average value and slope will cause no consistent error greater than $0.05 - 0.07 \mu\text{g}$. (It's entirely possible that a given bias could be in error more than this, but it is likely that the biases on either side would not.) In addition, uncertainties in scale factors, knowledge of the center-of-gravity, and rotation rates contribute to errors. These errors could be cumulative, but most probably are not. Estimates of their error contributions are listed in Table 2.

Table 2

ACCELERATION ERRORS			
Quantity	$x_b (\mu\text{g})$	$y_b (\mu\text{g})$	$z_b (\mu\text{g})$
scale factor	.030	.020	.060
center-of-gravity	.035	<.020	.022
rotation rates	.070	.020	.060

At this time, there remain two unresolved questions from the analysis. First, what is the source of the unpredictable acceleration in the x direction? The x axis signal offset is clearly too large to be attributable to aerodynamics based upon an assessment using data from Ref. 6. In order for gravity-gradient and rotational effects to generate the unforeseen acceleration, the center-of-gravity would have to move about 40 in., which is unrealistic. However, it would take only a few ounces of force exerted on the Orbiter to produce this effect (since 1 oz. = 0.26 μ g). A component of this force has to be exerted in the positive x direction, which would occur with a gas leak in the opposite, i.e., negative x direction.

The second question (which is most likely related to the first) is: What is the cause of the 26 hour oscillations seen in both the x- and z- axes? This oscillation in the z direction would certainly require that a gas leak has a component in the z direction. Since the phase of the oscillation in the z axis is 180° with respect to the x axis, the z force component has to be exerted on the Orbiter from its underside. Therefore, the leak would be directed downward as well as backward from the Orbiter. Of course, if there is a continuous leak in the plane of the orbit, then the orbit itself would undergo a slight change. There is a slight change in orbit conditions (see Fig. 2). But, at this time, it is not known if the observed change in orbit is due to a leak, a result of cumulative attitude-keeping jet firings, or simply natural phenomena such as tidal effects, etc.

Rechecking the data, its processing, and calibration revealed no errors. The bias values for both x- and z-axes show no anomalies. Also, the signals calculated concurrently with the biases are in good agreement with the data once the data signals are adjusted for bias. Although no definitive explanation exists at the present time, all evidence indicates that both effects are real and should be included in the acceleration environment.

Summary

The OARE data on STS-50 during the time period 1^d 14^h to 3^d 14^h MET (38^h to 86^h MET) have been examined in detail and absolute acceleration levels have been derived at the location of the OARE, the orbiter center-of-gravity, and the STS-50 spacelab Crystal Growth Facility.

The tri-axial OARE raw acceleration measurements (i.e., telemetered data) during the interval have been filtered using a 2000 point trimmed mean filter moved every 250 points (OARE sample rate is 10 samples/s). This process removes large acceleration spikes due to thrusters, etc. and reduces the noise. The 10 OARE measured biases in each channel during the 2^d interval were analyzed and applied to the filtered data. Similarly, the x-axis scale factors were also analyzed and applied to the data. Both y- and z- axis scale factors were determined in a separate process (using the OARE maneuver data) and subsequently applied to the data. All known significant corrections at the OARE location (i.e., gravity-gradient effects from both vertical and horizontal displacements, and rotational effects) were removed from the filtered data in order to produce the aerodynamic signals along the 3 body axes. However, the results indicate that there is a force of unknown origin being applied to the Orbiter in addition to the aerodynamic forces. The force characteristics are such that they produces a cyclic acceleration with a period of ~26 hours and an amplitude of 0.1 to 0.2 μg residing on top of a magnitude of about 0.5 μg , in the plane of the orbit. Upon re-examination of the OARE instrument, there is no evidence that the equipment is malfunctioning. Further, all known gravitational and electromagnetic forces have been reexamined and none produce the observed effect. Thus, it is tentatively concluded that the Orbiter is creating the environment observed (e.g., an oscillatory gas leak

of a few ounces of force in the aft direction could produce the effect). Obviously, this situation requires further investigation.

The aerodynamics data (with the unknown force) are mapped to the Crystal Growth Facility (CGF) location by adding the adjustments to the measurements for gravity-gradient and rotational effects. The enclosed Fig. 13 shows the final results. The acceleration along the x-axis ($\sim 0.5 \mu g$) is dominated by the acceleration created by the unknown force, possibly the Orbiter itself. The acceleration along the y-axis is slightly negative ($\sim 0.2 \mu g$) mostly due to aerodynamics and gravity-gradient horizontal displacement effects. The z-axis acceleration shows the diurnal atmospheric effect, about $0.6 \mu g$ s. This effect is observed in conjunction with the 26-hour oscillation caused by the z-component of the unknown force.

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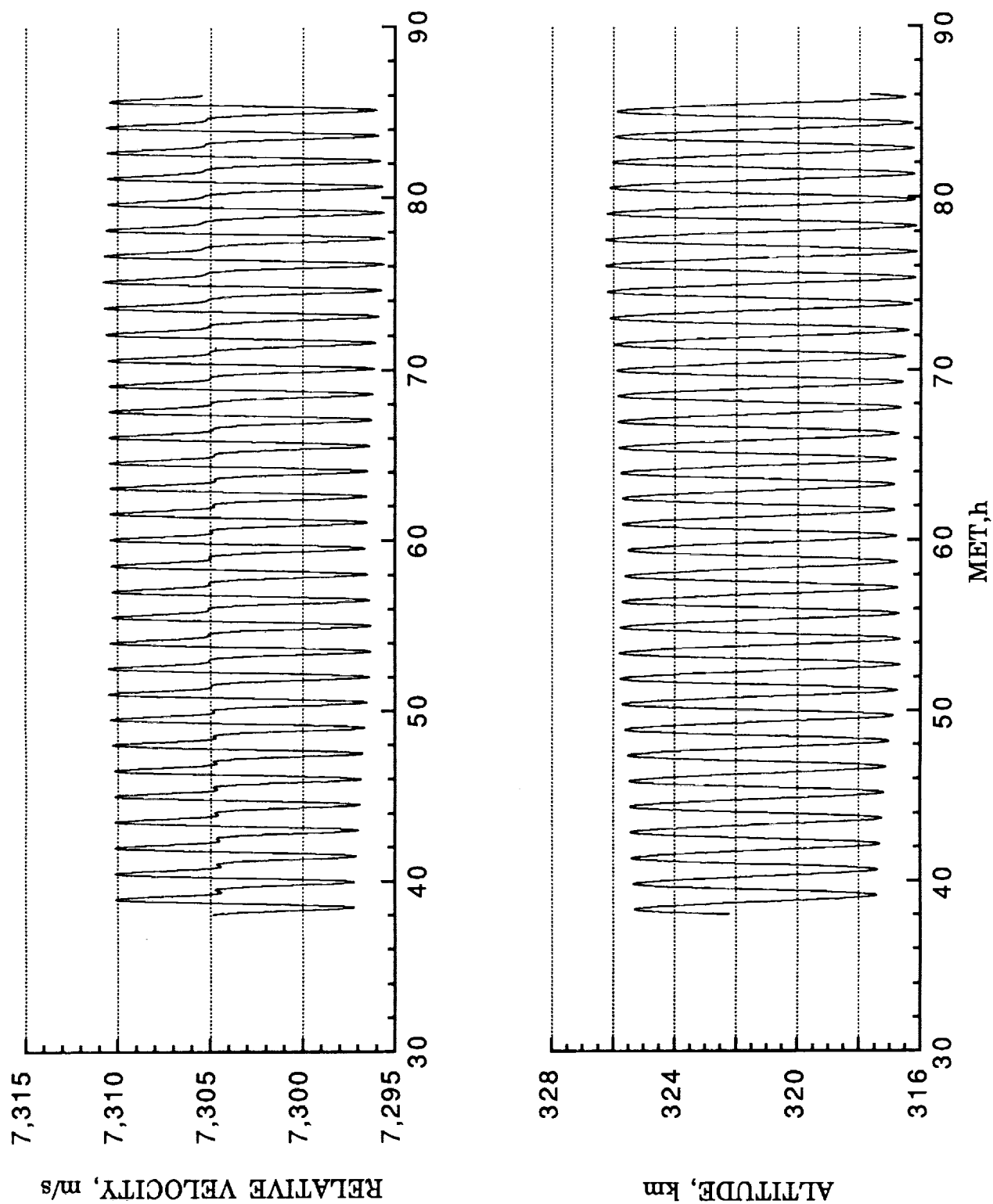


Fig. 1 Orbiter relative velocity and altitude time history.

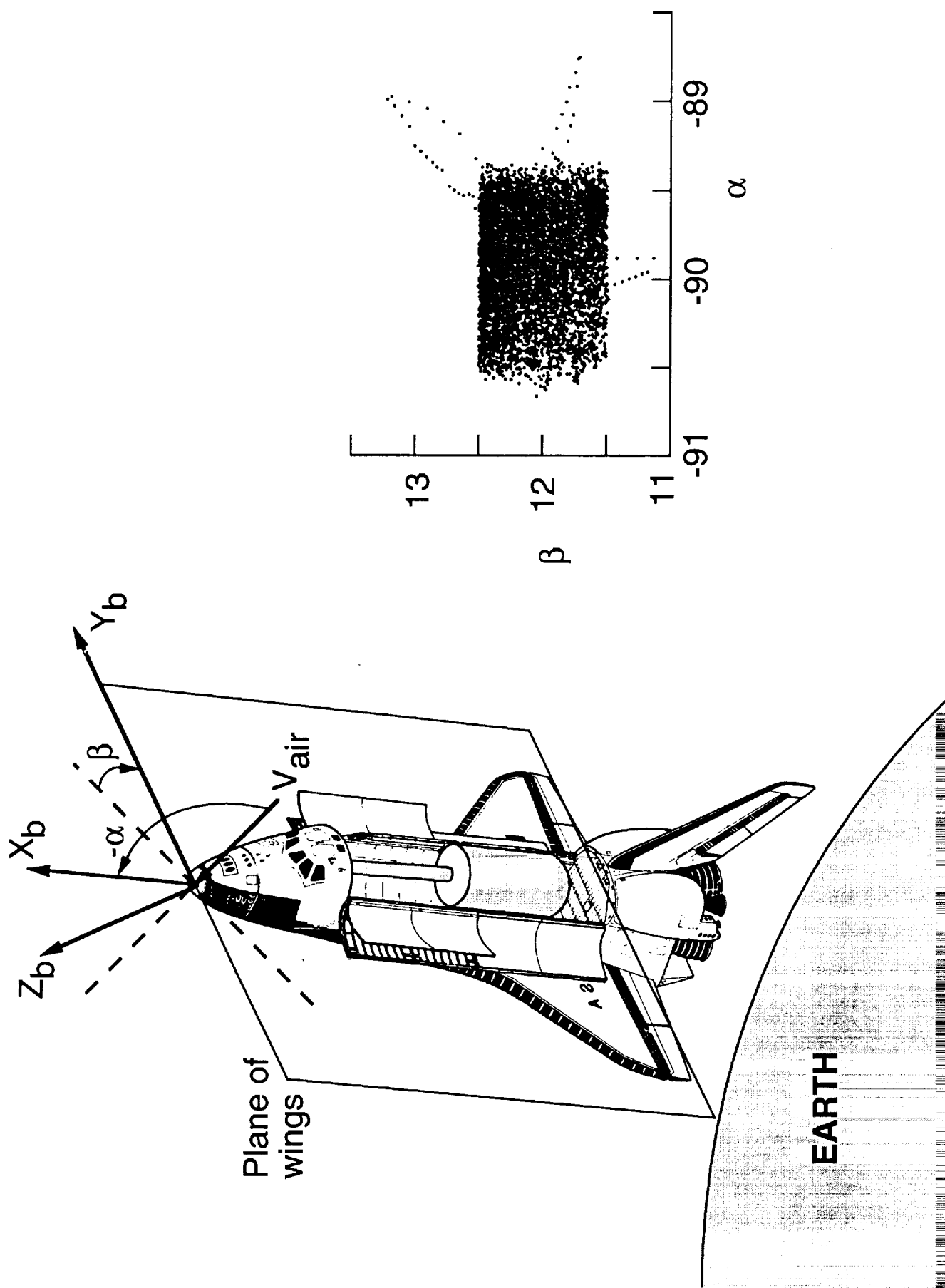


Fig. 2 Orbiter orientation and measurements.

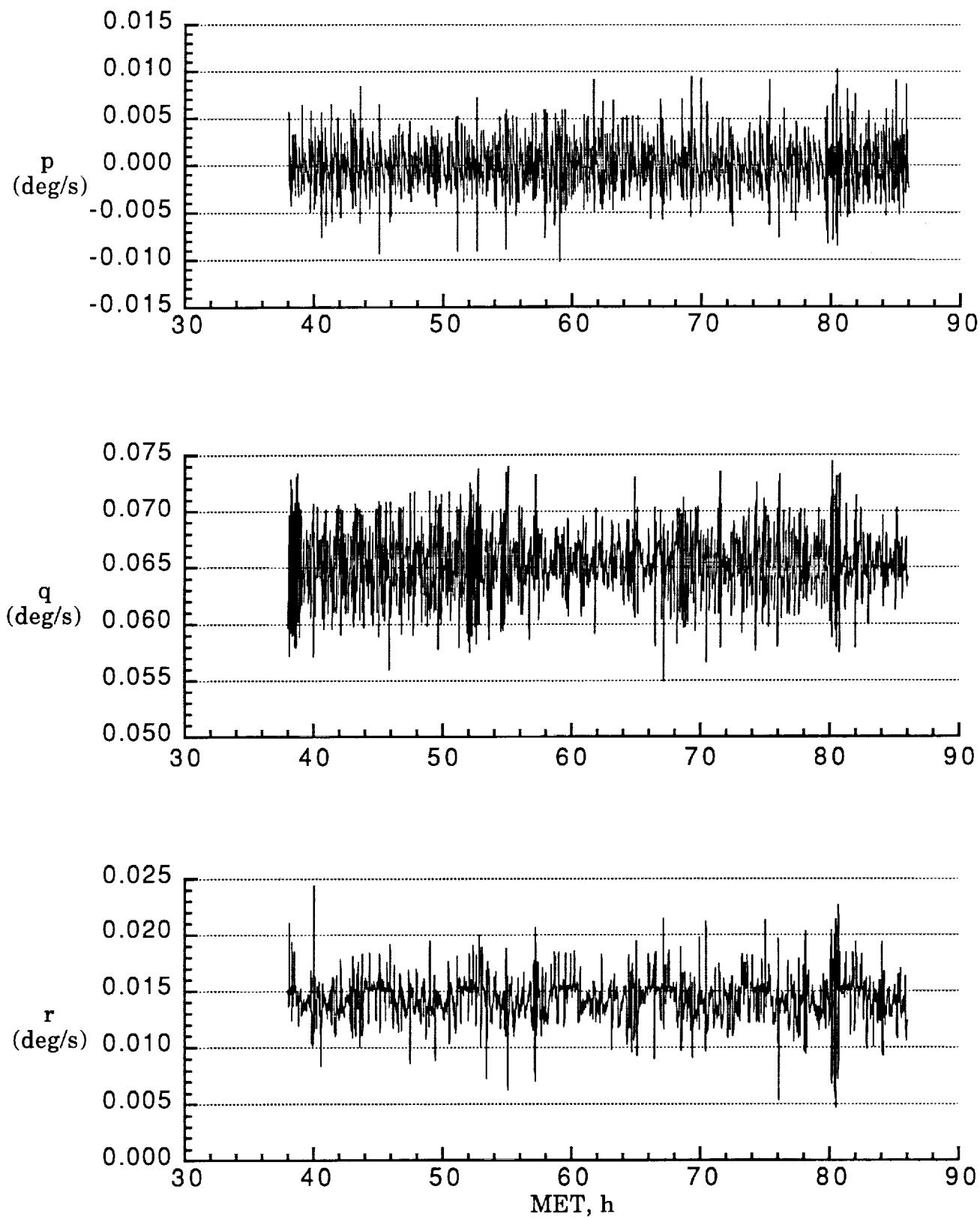


Fig. 3 Orbiter angular body rates.

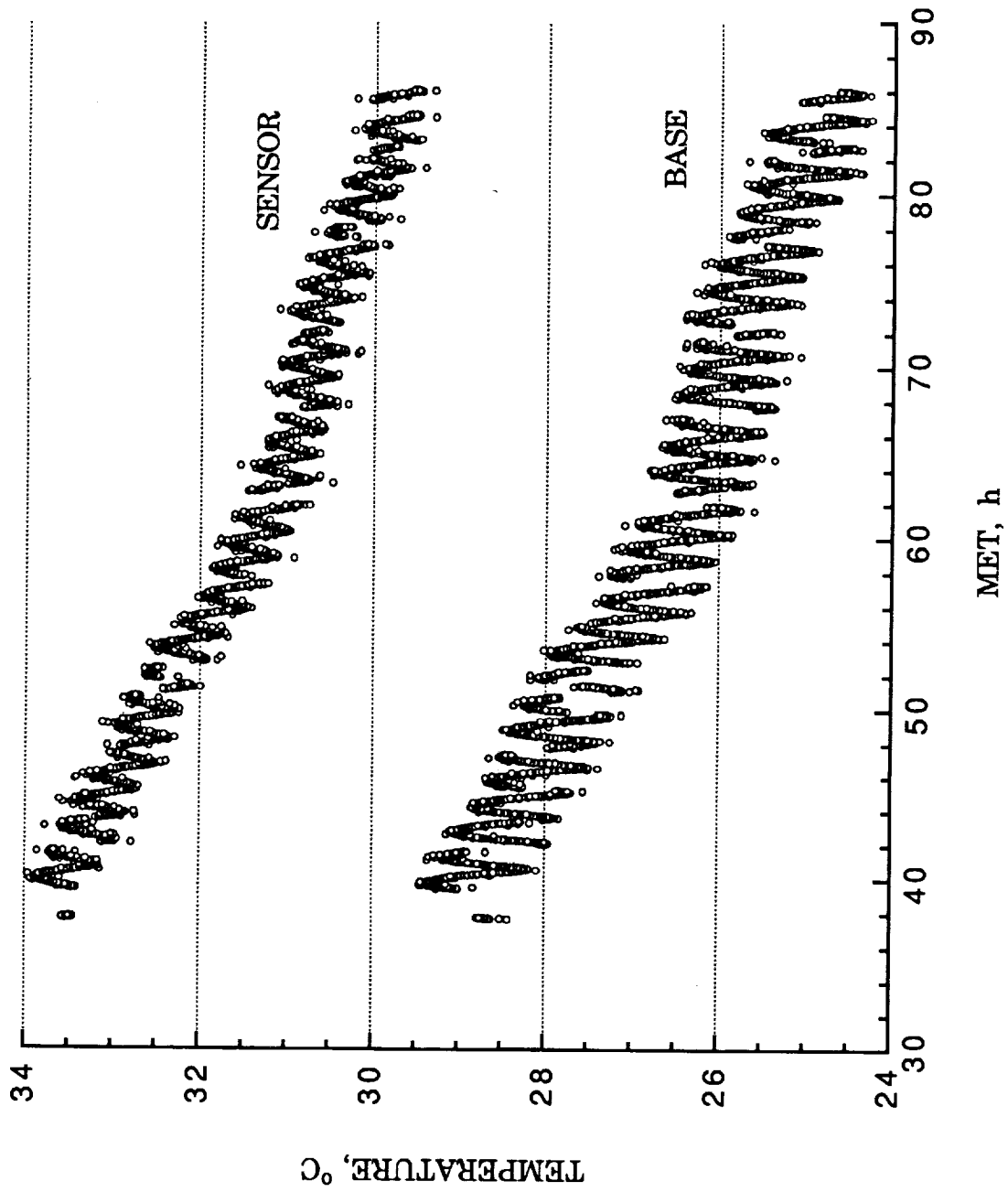


Fig. 4 OARE sensor temperature measurements.

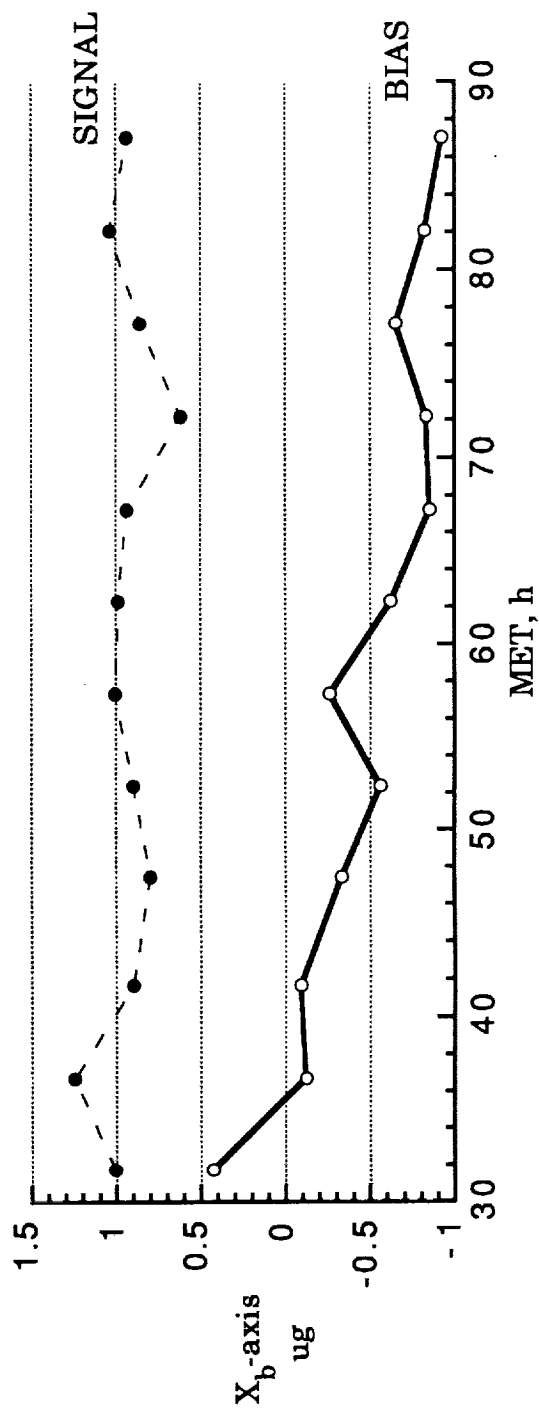
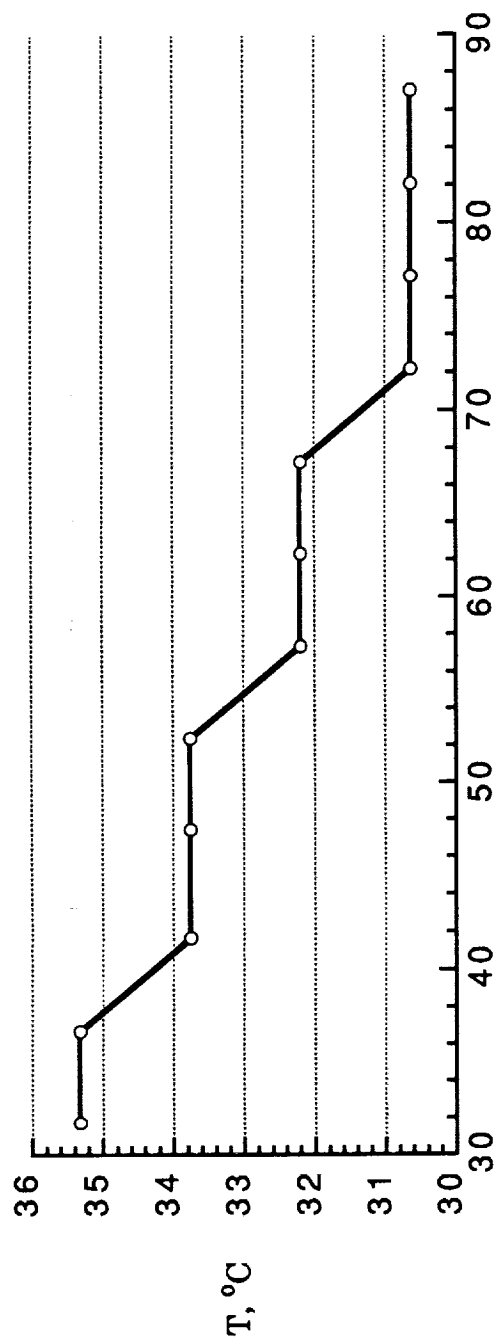


Fig. 5 X body axis sensor temperature, bias, and signal measurements.

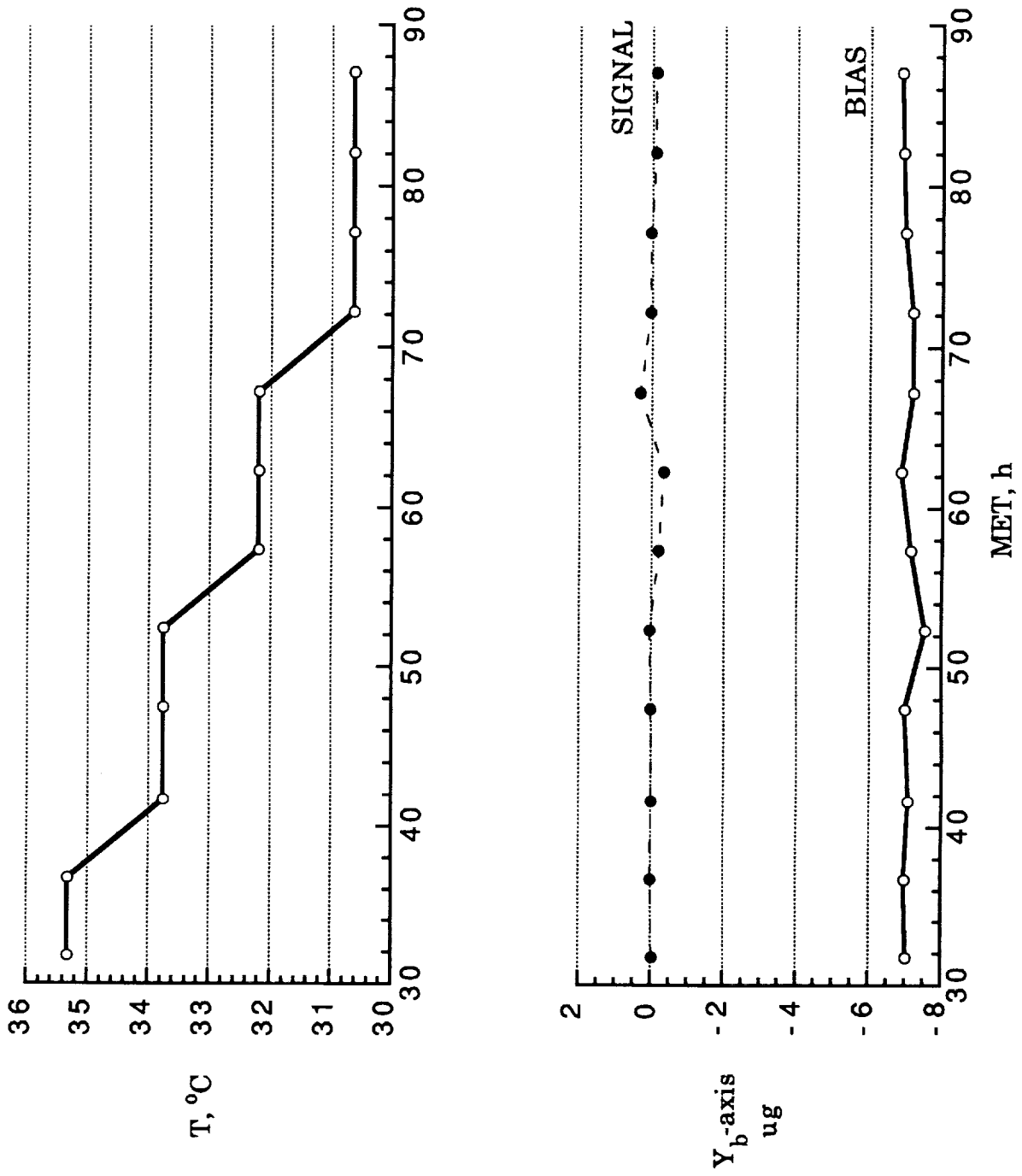


Fig. 6 Y body axis sensor temperature, bias, and signal measurements.

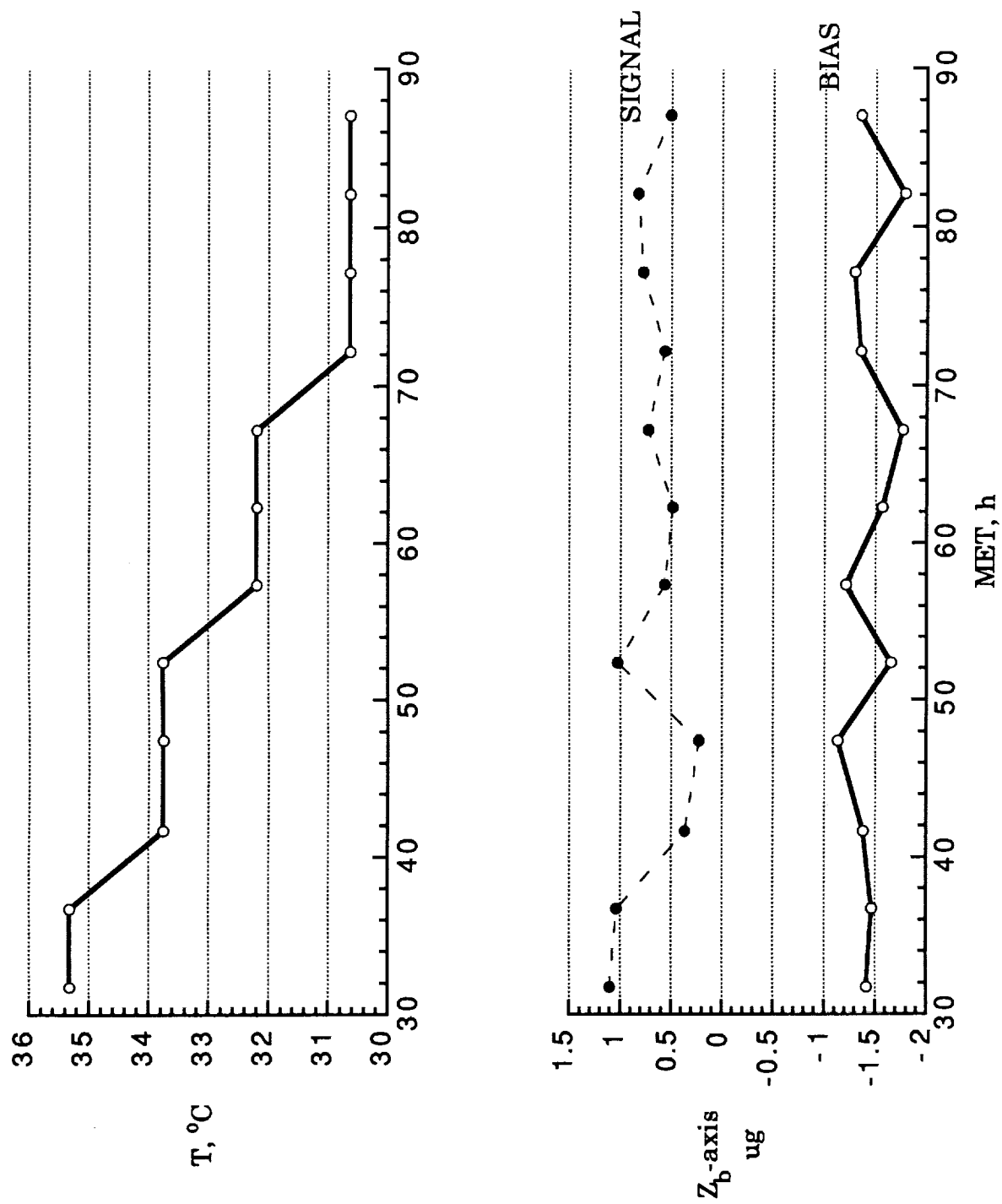


Fig. 7 Z body axis sensor temperature, bias, and signal measurements

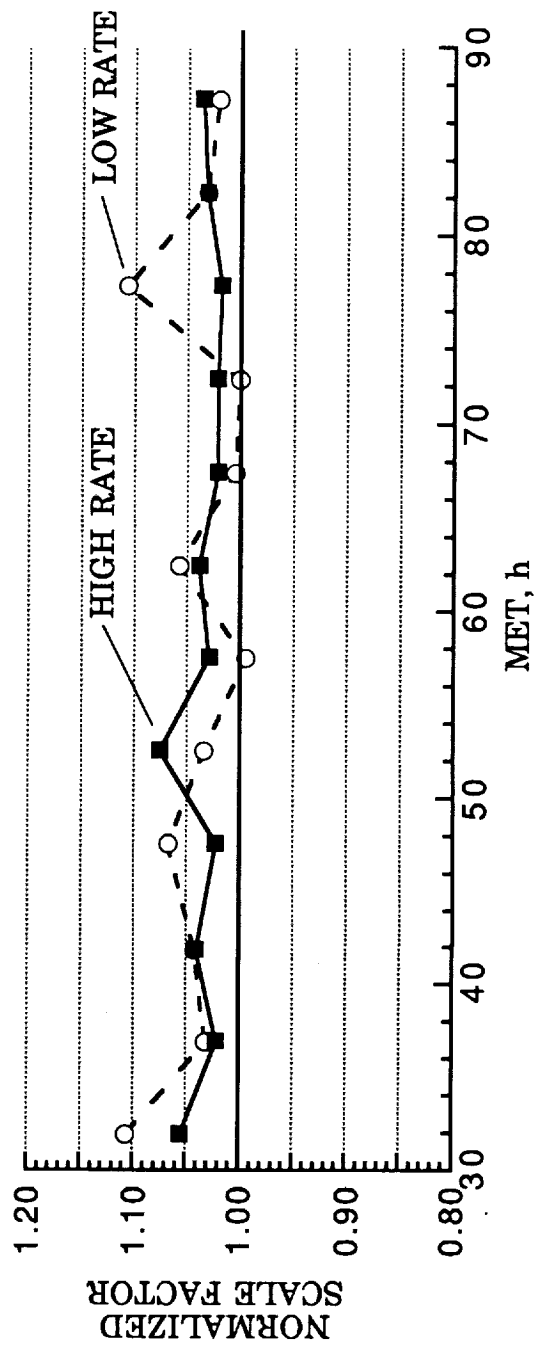
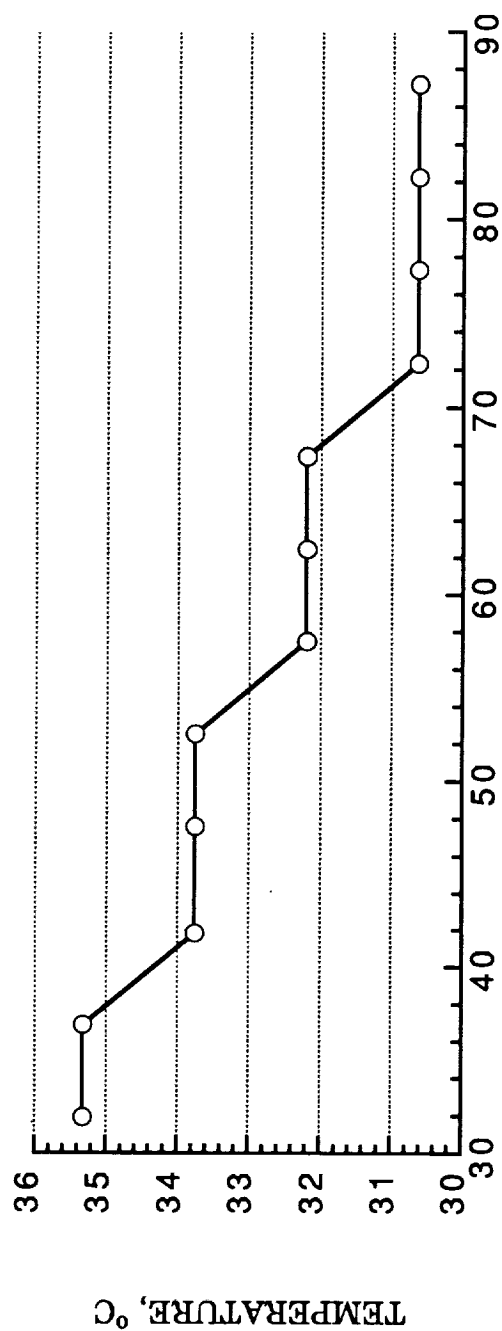


Fig. 8 X-axis C-range scale factor measurements

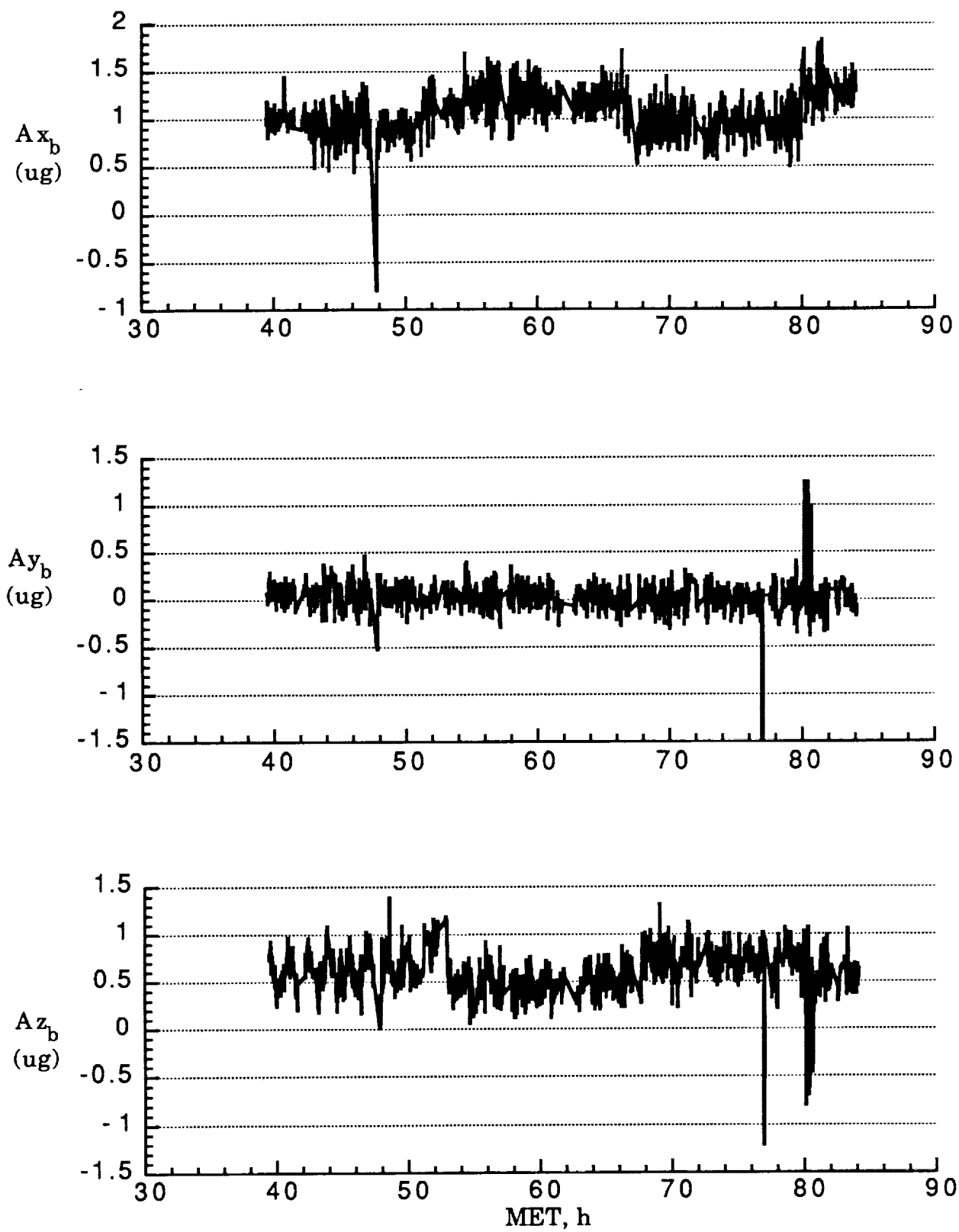


Fig. 9 OARE body axes measurements at the OARE location

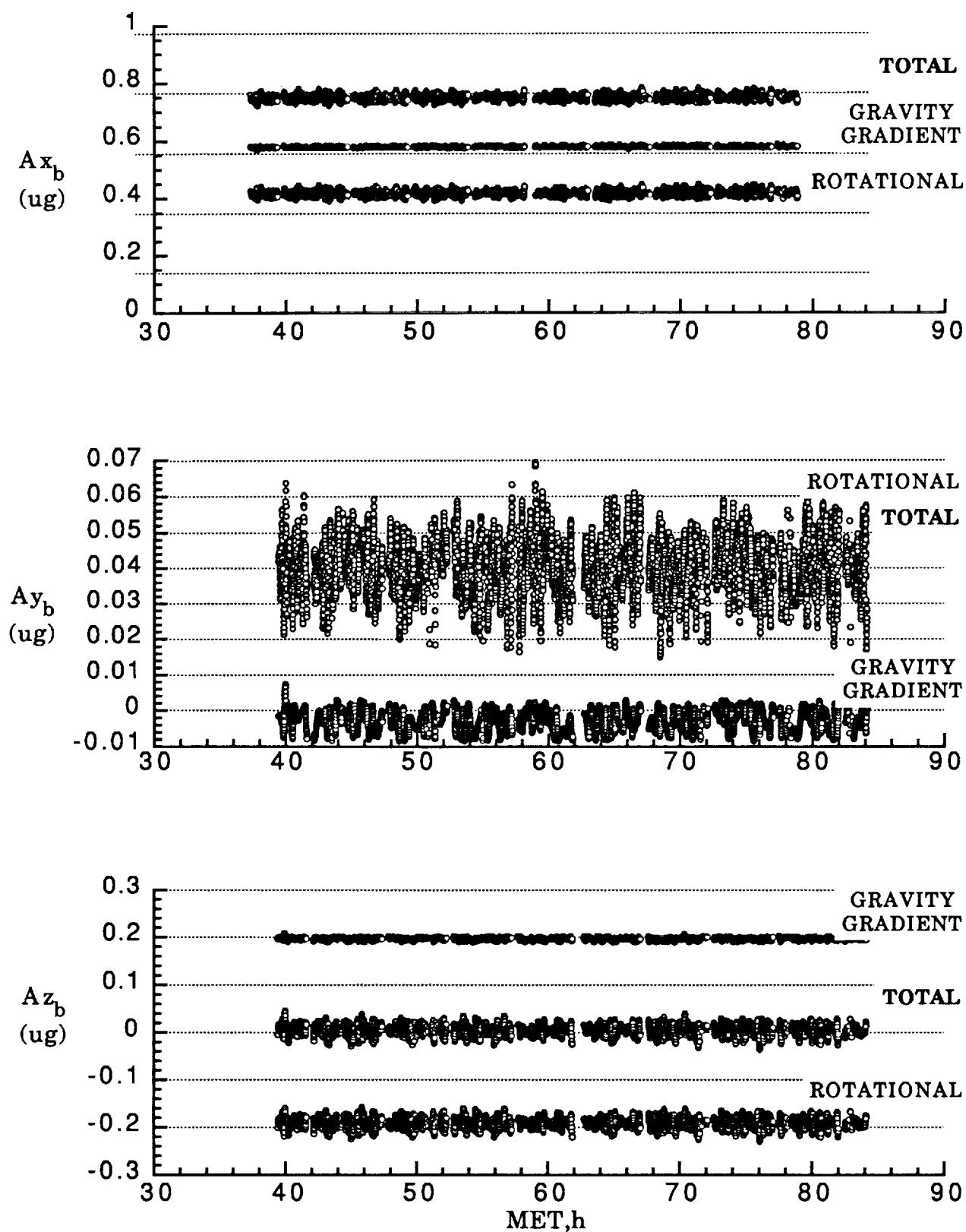


Fig. 10 Gravity gradient and rotational accelerations from Orbiter measurements at the OARE location

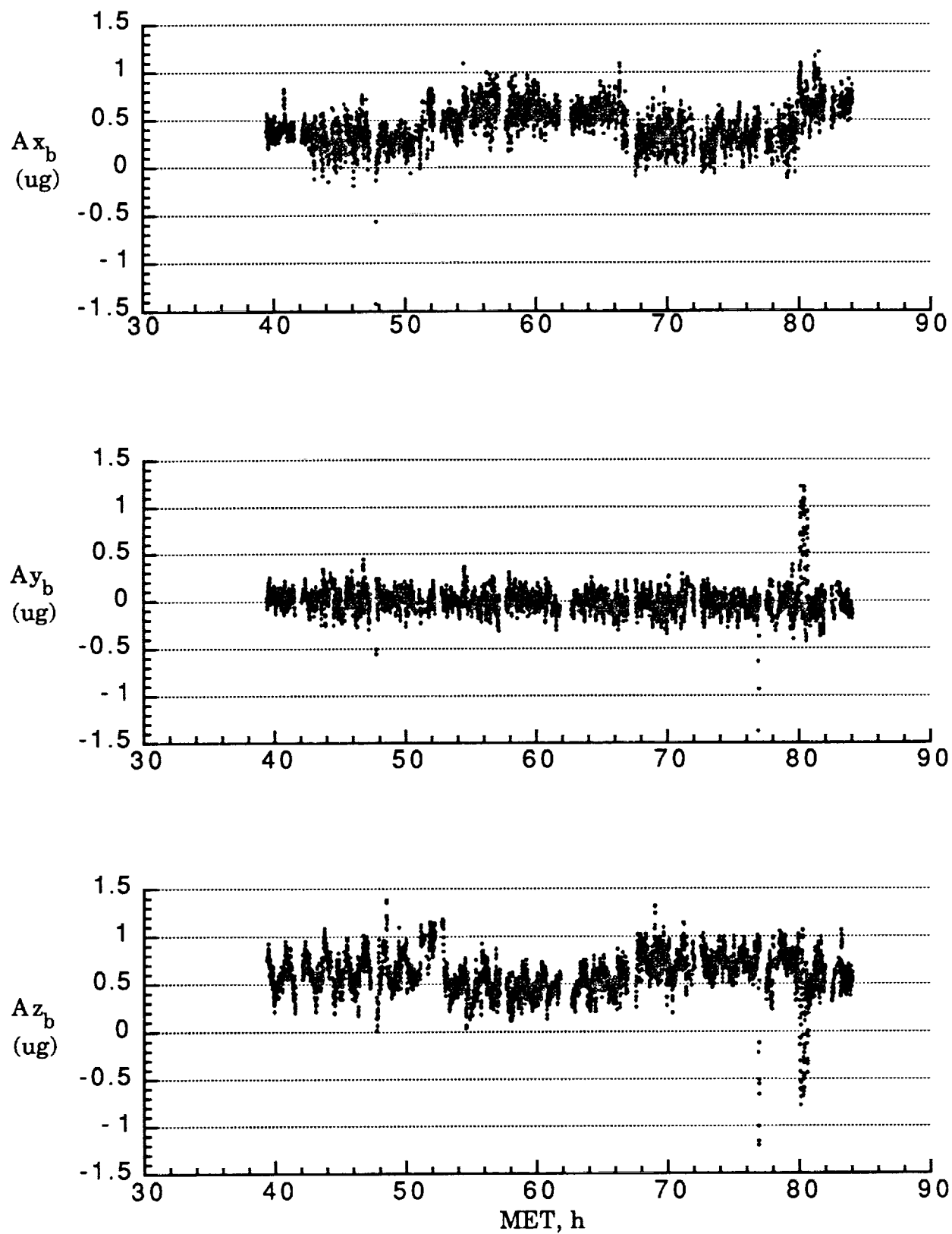


Fig. 11 OARE measurements at the center of gravity.

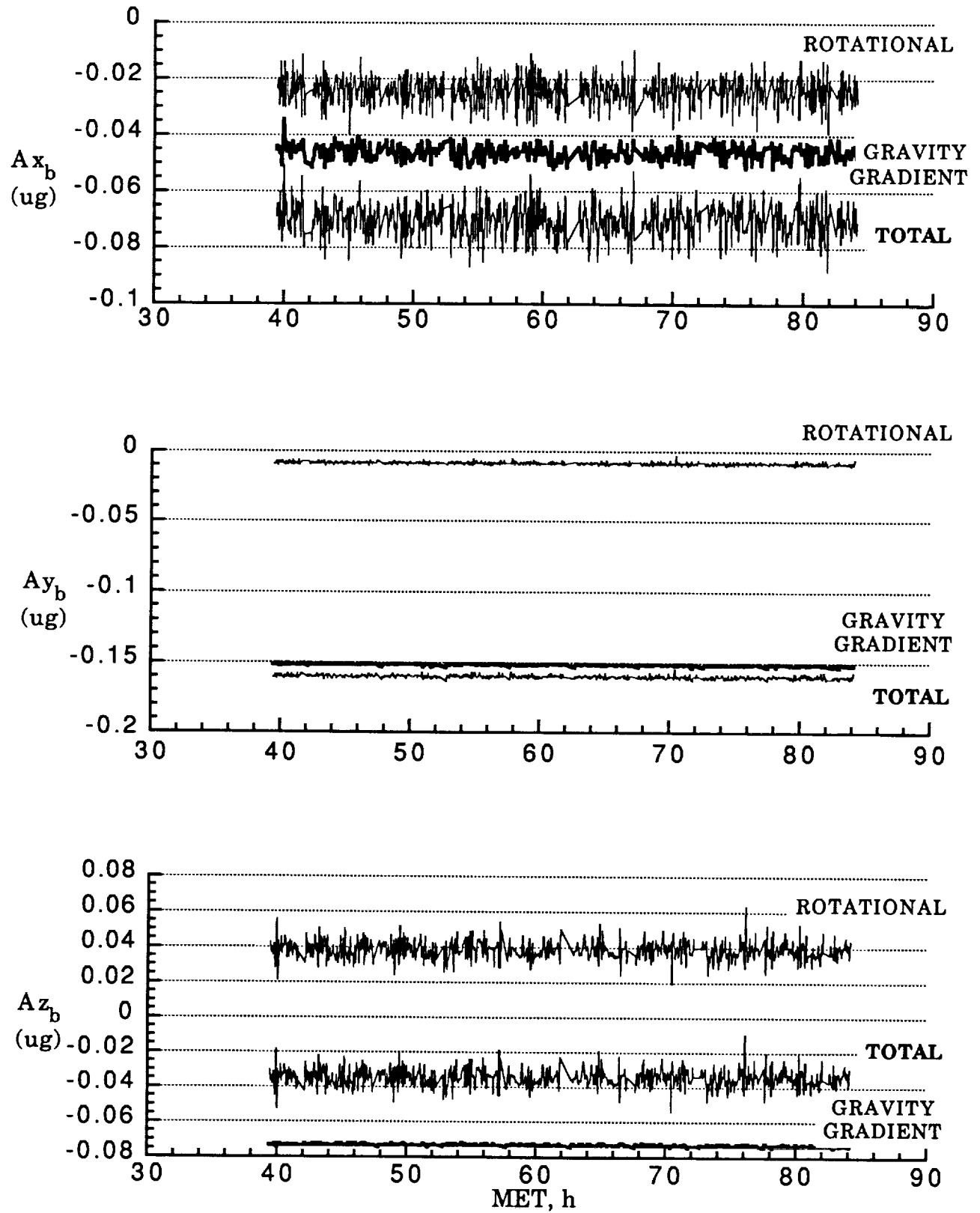


Fig. 12 Gravity gradient and rotational accelerations from Orbiter measurements at the CGF location.

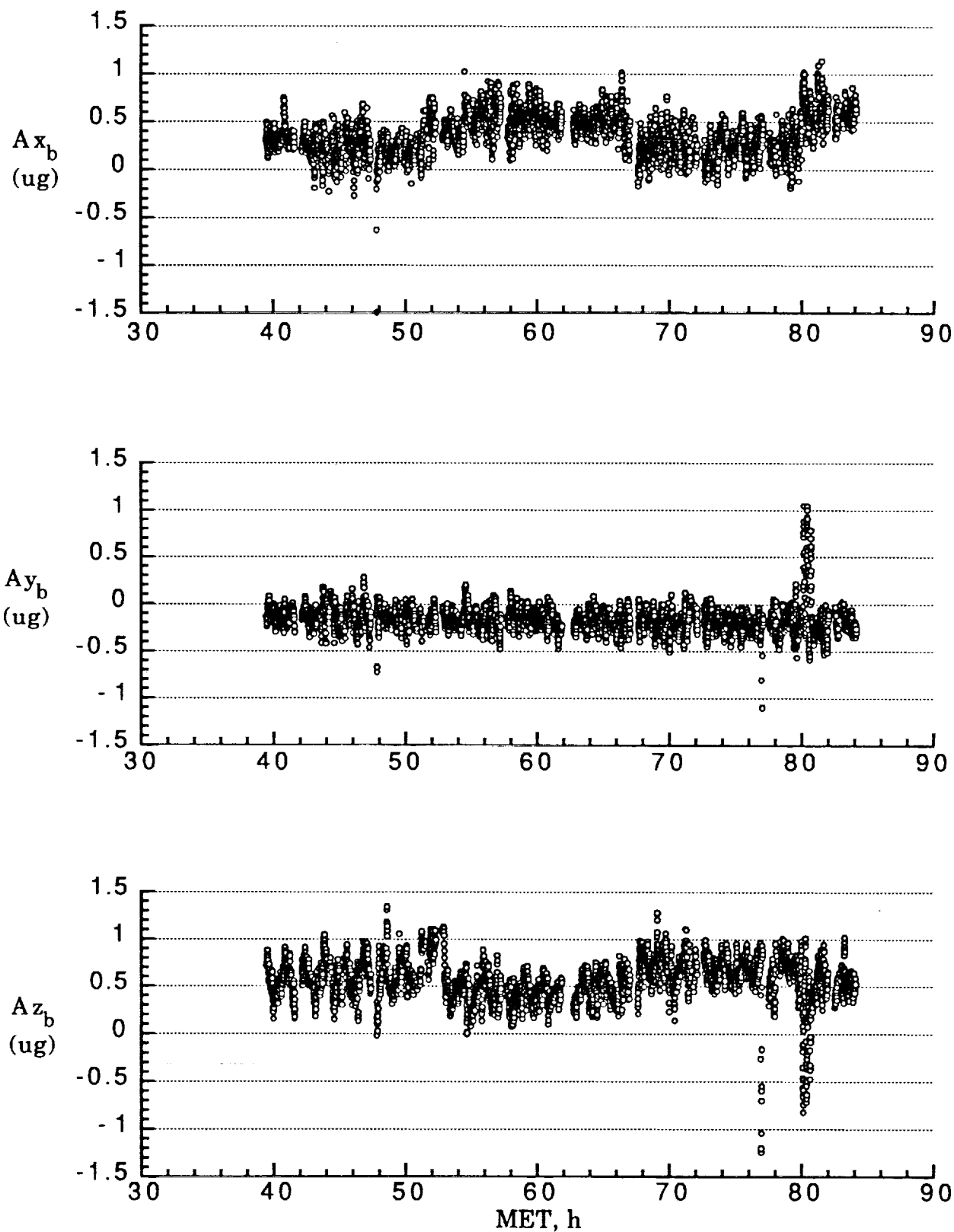


Fig. 13 Body axes accelerations at the CGF location ($X_0=1086.00$, $Y_0=44.39$, $Z_0=395.45$) using OARE data.

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13. ABSTRACT (Maximum 200 words) On-orbit OARE data on STS-50 has been examined in detail during a 2-day time period. Absolute acceleration levels have been derived at the OARE location, the orbiter center-of-gravity, and at the STS-50 spacelab Crystal Growth Facility. The tri-axial OARE raw acceleration measurements (i.e., telemetered data) during the interval have been filtered using a sliding trimmed mean filter in order to remove large acceleration spikes (e.g., thrusters) and reduce the noise. Twelve OARE measured biases in each acceleration channel during the 2-day interval have been analyzed and applied to the filtered data. Similarly, the <i>in situ</i> measured x-axis scale factors in the sensor's most sensitive range were also analyzed and applied to the data. Due to equipment problem(s) on this flight, both y- and z- axis sensitive range scale factors were determined in a separate process (using the OARE maneuver data) and subsequently applied to the data. All known significant low-frequency corrections at the OARE location (i.e., both vertical and horizontal gravity-gradient, and rotational effects) were removed from the filtered data in order to produce the acceleration components at the orbiter's center-of-gravity, which are the aerodynamic signals along each body axes. Results indicate that there is a force of unknown origin being applied to the Orbiter in addition to the aerodynamic forces. The OARE instrument and all known gravitational and electromagnetic forces have been reexamined, but none produce the observed effect. Thus, it is tentatively concluded that the Orbiter is creating the environment observed.				
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